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ORIGINAL RESULTS

Detection possibilities of hostless intergalactic supernova remnants with Square Kilometre Array

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Abstract. Possibilities to detect hostless supernova remnants (hl-SNR) in intergalactic medium using the 1 GHz band of the Square Kilometre Array (SKA) are discussed. The optical detection rate of the hl-SN constrained from the Sloan Digital Sky Survey is used to predict a number of detectable hl-SNRs in the radio band. With an anticipated detection sensitivity ($\sim 1\ \mu$Jy) and angular resolution ($<1''$) with the SKA, a significant number of hl-SNR are expected to get detected in the nearby galaxy groups, such as local group, Virgo, Fornax and Eridanus. A few very luminous hl-SNR may also be detected in the Coma cluster and other rich galaxy clusters up to about 100 Mpc distance. The identification of individual SNRs against other background radio sources will require sub-arcsec angular resolution at 1 GHz to resolve the characteristic circular morphology of the radio SNRs in nearby groups. At larger distances, where individual SNR cannot be resolved, a population of hl-SNR may also be constrained statistically in a small region, by estimating excess unresolved radio sources without a known optical host in a group or cluster, compared to the number density of the background radio sources at μJy flux level.

Keywords. Supernovae remnants—galaxy groups—galaxy clusters—Square Kilometer Array—radio surveys.

1. Introduction

A significant number of hostless supernovae (hl-SN) have been detected in various optical surveys, where a fixed region of the sky was observed many times over several months of period with a cadence of a few days or weeks. Some of these observations were targeted on individual massive galaxy clusters (e.g., Gal-Yam *et al.* 2003; Sand *et al.* 2008, 2011; Dilday *et al.* 2010), while the Sloan Digital Sky Survey (SDSS) supernova program (Friemann *et al.* 2008) covered a large region of about 300 deg^2 sky. These surveys detected several supernovae, majority of these were hosted in galaxies. However, a significant number of supernovae in these surveys were clearly not hosted in any known optical galaxy and therefore, termed as hostless. The hl-SN are sometimes also called as intergalactic or intracluster supernovae, if detected in galaxy groups or clusters, respectively. The follow-up observations of four hl-SN after more than 3 years from the epoch of the peak brightness, no persistent optical counterparts such as galaxies were identified for three supernovae using the HST with detection limits M_R between -9 and -10 mag (Graham *et al.* 2015). These observations ruled out the possibility of any associated faint galaxy, which was not detected when the supernovae were bright.

The hl-SN are likely to find their origins in stars in the intergalactic medium (IGM) or intracluster medium (ICM), which can have a significant stellar population in the tidal debris resulting from multiple tidal interactions and mergers of galaxies in groups and clusters. The diffuse faint intracluster light (ICL) and tidal streamers composed of stars in IGM and ICM have been detected in several galaxy clusters and groups (e.g., Zibetti *et al.* 2005; Krick & Bernstein 2007), confirming that stars exist in the IGM and ICM. The tidal interactions are fairly common in groups and clusters, and known to be

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affecting galaxy evolution via removal of stars and gases from galaxies (see e.g., Omar & Dwarakanath 2005). As various nomenclaturess have been used in the literature regarding galaxy groups and clusters, we will refer the known structures by their common names (e.g., local group, Fornax, Coma cluster) and in general, the groups are referred here as less massive ($<10^{13}$ $M_\odot$) structures compared to the clusters, which are more massive structures.

Mainly, the hl-SN are expected to be type-Ia supernovae, which are presently understood as a result of an explosion of a white dwarf in a binary system. The explosion takes place when the white dwarf accretes sufficient mass from the companion star, so that a runaway thermonuclear fusion reaction becomes inevitable. The high mass stars (>8 $M_\odot$) responsible for type-II supernovae are short-lived and hence, the supernovae type-II rate declines very fast within a few tens of Myr period after a major episode of star formation. Therefore, the hostless type-II SN are extremely rare to detect. Detecting hl-SN events (hereafter hl-SN means type-Ia SN only) in the optical bands can be challenging and time consuming as supernova afterglow will normally become optically faint in a few weeks of time. Therefore, a large number of groups and clusters need to be searched with high cadence to detect hl-SN. On the other hand, evolved remnants of such supernovae can glow in the radio bands after a few hundred years of the explosion when the supernova enters the Sedov phase, which may typically last for 10^4–10^5 years. Therefore, a search for the hostless supernovae remnants (hl-SNR) in the radio bands should be easier and it may result into indirect confirmations of a large number of past hl-SN events, which otherwise cannot be detected at present epoch in the optical bands.

An indirect confirmation of hl-SN in galaxy groups and clusters via detections of hl-SNR at present epoch can be important for many reasons. Domainko *et al.* (2004) and Zaritsky *et al.* (2004) argued that the intracluster supernovae are required to match the observed excess iron (Fe) abundance in many cool-core clusters. The intracluster supernovae have also been considered efficient sources of heating and turbulence in the ICM (Valdarnini 2003; Domainko *et al.* 2004; Tang & Wang 2005). Omar (2019) discussed a possibility that the radio emission from radio mini-halos and the low-radio surface brightness structures on a few hundred kpc-scales associated with the brightest cluster galaxies in many cool-core galaxy clusters, may also be explained in terms of the relativistic electrons accelerated in multiple intracluster SNR. A direct detection of hl-SNRs in nearby galaxy groups and clusters will strengthen all such conjectured possibilities.

At present, no hl-SNR has been detected in radio. Previously, Maoz *et al.* (2005) discussed possibilities to detect hl-SNR in both optical and radio bands. Omar (2022) has recently argued that some of the circular radio sources termed as Odd Radio Circles (ORCs) without optical counterparts (Norris *et al.* 2021a), detected in, Australian Square Kilometre Array Pathfinder—Evolutionary Map of the Universe (ASKAP-EMU) survey (Norris *et al.* 2021b) could be the hl-SNR in the local group or its immediate neighbour groups of galaxies, namely, the Sextans group, Sculptor group, IC 342/Maffei group and M 81 group.

This paper explores possibilities to detect hl-SNR using the SKA. The main aims of this paper are to find: (i) whether the number of estimated hl-SNR in nearby galaxy groups is significant or not and (ii) whether hl-SNR can be detected with the SKA sensitivity. Section 2 provides a rough estimate for the numbers of hl-SNR in some nearby groups and clusters based on the hl-SN detection rate constrained from the SDSS-SN survey. Different radio detectability scenarios are discussed in Section 3.

2. Hostless supernovae rates

It is not possible to accurately constrain hl-SN rate in a particular group or cluster of galaxies. An exact estimate is required to constrain several parameters, such as star-formation history over a few Gyr period, galaxy–galaxy and group/cluster merger histories, stellar mass residing in the IGM or ICM and supernova delay-time distribution (DTD). The SN-DTD predicts decrease in the SN-Ia rate as a function of time over a few Gyr period from the last major star-formation activity in the group or cluster (see e.g., Friedmann & Maoz 2018). Most of the above parameters are often poorly constrained in majority of galaxy groups or clusters. Therefore, in absence of direct constrains of the SN-Ia rates in individual groups, results from large surveys aimed at detecting supernovae in groups and clusters can be used as the best alternative to predict an average SN-Ia rate in any massive structure.

A statistically significant estimate of the hl-SN rate came from an analysis, by McGee & Balogh (2010), of 59 supernovae detected in the low redshift ($0.1 < z < 0.2$) galaxy groups covered in the SDSS-SN survey (Friemann *et al.* 2008), and carried over ~ 300 deg^2 sky-area over a total span of 5 years with a total observation period of nearly 9 months. The entire surveyed area of the sky was observed multiple times during the total period of observations. The average sampling rate was nearly 5 nights per field. Considering large surveyed area with an adequate sampling rate for detecting supernovae with a 2-m class telescope up to a redshift of ~ 0.2, the SN rates obtained from the SDSS-SN survey can be considered robust and statistically significant. McGee & Balogh (2010) identified 22 hl-SN in 1401 galaxy groups with their combined mass of 5.4×10^{16} $M_{\odot}$. The qualifying criterion for a SN to be host-less, was that it should be outside a nearby galaxy by at least a distance, which is twice the galaxy size measured at 90% of the galaxy light. These SN detections over total mass of the groups in total observing period of the SDSS-SN survey translated into a hl-SN rate of ~ 5400 SN per million year in a group mass of 10^{13} $M_{\odot}$. As the SN rate depends on mass of the group, it can be scaled up or down according to the mass of galaxy groups. Although, these estimates are derived from the observations of galaxy groups, we will use it for nearby galaxy clusters also.

The SNIa rate at an epoch also depends on the DTD parameter. The DTD of SNIa rate has been shown to vary nearly as $1/t$; where t is time (Gyr) from the last major star-burst epoch (see e.g., Maoz *et al.* 2012). Therefore, the SN-Ia rate in a galaxy cluster or group can vary by one to two orders of magnitude depending upon the redshift. Hence, if the SN-Ia rate constrained from a redshift bin 0.1–0.2 is used to predict SN-Ia rate at $z \sim 0$, the decline in the SN-Ia rate needs to be considered assuming that a major starburst event in a cluster happened beyond the redshift of 0.2. This decline is estimated here as ~ 2 at $z \sim 0$ compared to that measured in the redshift bin 0.1–0.2 by McGee & Balogh (2010).

3. Radio detectability scenarios of hl-SNR with SKA

The radio brightness of a SNR depends on various parameters, namely, age, density and temperature of the ambient medium, where the SN shock-wave is expanding. The theoretical frameworks for SNR evolution normally consider four evolutionary stages, namely, the blast-wave expansion phase with constant velocity, the Sedov phase with constant energy, the snow-plough phase with constant momentum, and finally merging of SNR with the ambient medium (see Reynolds 2017). The density of the ambient medium in which the blast wave is expanding, plays an important role in the evolution of SNR. The size of SNR is expected to become larger in low-density medium than that in a denser medium. The acceleration of particles to the relativistic speeds takes place in the Sedov phase via a diffusive shock acceleration related Fermi process. Therefore, the radio bright phase of a SNR is delayed until the Sedov phase sets in. On the other hand, the temperature of the ambient medium controls the Mach number of the expanding shock, which can have initial velocity of $\sim 10^4$ km s^{-1} and later 10^4–10^2 km s^{-1} in the Sedov phase as the blast wave gradually slows down. Since the sound speeds are in the range of 10^2–10^3 km s^{-1} in typical conditions in the IGM and ICM, the shocks experience low Mach numbers of the order of a few and almost always < 10. The particle acceleration efficiency varies very strongly with the Mach number in low Mach number (<10) regimes (see e.g., Hoeft & Bruggen 2007), hence, the radio brightness evolution will vary as a function of physical conditions of the ambient medium. As the sound speed increases with temperature as $T^{0.5}$, the hotter regions, such as the cores of massive clusters are expected to be the least efficient in particle acceleration compared to relatively less hot IGM and the interstellar medium (ISM).

Tang & Wang (2005) studied evolution of SNR blastwaves in low-density hot medium typical of those in galaxy groups and clusters. The Sedov phase responsible for the particle acceleration is expected to last for about 10^4 years in such conditions. The early works on SNR evolution in low densities were carried out by Tomisaka *et al.* (1980) and Higdon & Lingenfelter (1980). Bhattacharya (1990) discussed radio brightness of SNR evolving in low-density warm ISM in the cavities created by the stellar winds from the supernova-progenitor massive star. Pavlovic *et al.* (2018) worked out radio surface brightness evolution of SNR as a function of ambient density via detailed simulations. We consider typical densities in the IGM and outer regions of clusters as 10^{-4} cm^{-3}. In such a density, the diameter of an evolved (i.e., in late Sedov phase) SNR is predicted to be ~ 200 pc when the radio surface brightness approaches a value below 10^{-22} W m^2 Hz^{-1} sr^{-1} (Pavlovic *et al.* 2018). Upon further expansion in the late phase, surface brightness falls rapidly (brightness-diameter slope between -4 and -6) and the SNR is not detectable. This stage is achieved in about 10^4 years and beyond that, the radio surface brightness will fall below the detection limit of the telescope. In such a case, based on the hl-SN rate estimated from the SDSS-SN survey in the previous section, one expects about 25 hl-SNR and 250 hl-SNR to remain visible in $z \sim 0$ groups/clusters of masses 10^{13} $M_{\odot}$ and 10^{14} $M_{\odot}$, respectively. This estimate includes the number decrement factor of 2 at $z \sim 0$ as estimated in the previous section. This estimate has several uncertainties, e.g., the radio surface brightness of SNR varies as a function of local density and temperature of IGM and so the radio detectability period of SNRs can be lower or higher than the assumed value of 10^4 years depending upon the physical conditions in the IGM or ICM. Nevertheless, the expected number of SNRs in typical group environments and physical conditions is significant.

It may be noted that the magnetic fields in the IGM or ICM do not play an important role in the early phase of SNR evolution as magnetic fields in the SNR are amplified in the shocks. At very late stages ($\geq 10^6$ years), the relativistic electrons will still be emitting at low-frequency radio bands, however, this emission will become very diffuse and may contribute to Mpc-scale radio emission seen in several galaxy clusters (Omar 2019). At this stage, individual SNRs are not detected, however, their combined emission may appear as a radio mini-halo.

We use the anticipated sensitivities of the SKA provided in Braun *et al.* (2019) and the depths of some feasible radio surveys given in Norris *et al.* (2015) to explore possibilities of detecting radio SNRs. The anticipated performance of the SKA-1 is ~ 4.4 μJy per beam with $0.7''$ angular resolution at 1.4 GHz band in about 1 h of observation. A feasible large-area survey may obtain a 5σ detection sensitivity down to ~ 10 μJy in the SKA-1 phase with about an arcsec resolution and possibly down to ~ 0.5 μJy with the SKA-2 (or full-SKA) with an angular resolution of $\sim 0.1''$. As explained later in this paper, the most plausible way of detecting radio SNRs will be via identifying their characteristic morphologies (e.g., shell and circular ring). Therefore, the detection sensitivity for the partially resolved sources will decrease and the sensitivity estimates need to be adjusted by a factor equal to the number of resolving synthesized beams across the diameter of a SNR. We take this as three synthesized beams and so the sensitivity will degrade by a factor of three for the resolved cases.

The near 1 GHz radio luminosity of majority of Galactic SNR are found in the range of 10^{15}–10^{18} W Hz^{-1} (see e.g., Green 2004). We assume that the extra-galactic SNRs will also have similar radio luminosities and discuss here various detectability scenarios in the extra-galactic contexts for a canonical 200-pc size SNR in the low ambient density regions.

3.1 *Detections of individual hl-SNR*

The individual hl-SNRs can be identified against a background radio source population at μJy level if SNRs are partially resolved and their characteristic morphologies can be identified. Such detections can only be made in nearby groups or clusters, where the angular resolution will be sufficient to resolve the source. Such a radio SNR should not be co-located with any optical galaxy to qualify as hostless. The optical images from the existing deep optical surveys will be sufficient to identify a galaxy. The angular diameter of a 200-pc SNR in the Virgo cluster is expected to be $\sim 2''$. With an expected radio beam size of $0.7''$ and assuming three beams required to resolve a source, the SNR of 200-pc size can get resolved up to ~ 20 Mpc distance. With a beam size of $0.1''$, the SNR may get resolved up to a distance of ~ 140 Mpc.

The detections in all the resolved cases will depend upon the sensitivity of the radio survey. With a detection sensitivity of ~ 10 μJy, radio SNR with luminosities in the range 10^{15}–10^{18} W Hz^{-1} can be detected up to a distance of ~ 1 Mpc for the faintest SNR and up to ~ 30 Mpc for the brightest SNR. Similarly, with a detection sensitivity of ~ 0.5 μJy, radio SNR can be detected up to a distance of ~ 5 Mpc for the faintest SNR and up to ~ 140 Mpc for the brightest SNR. It is interesting and purely coincidental that both the resolution and flux sensitivity of the SKA enable detections of hl-SNRs up to nearly similar distance, i.e., ~ 140 Mpc. As the SKA will partially resolve some of the hl-SNRs, the total flux from a SNR will be divided over more than one beam and hence, the detection sensitivity will come down. Therefore, we can expect to detect partially resolved SNR only up to a few Mpc distance in the SKA-1 phase. In the full-SKA phase with the highest possible resolution and sensitivity, we can expect to detect a general population of hl-SNRs to a few tens of Mpc distance.

Therefore, in the SKA-1 phase, one can expect to detect hl-SNRs only in the local group of galaxies and its immediate neighbor groups. However, with the full SKA, one can expect to detect SNRs in some nearby rich galaxy groups, such as Virgo, Fornax and Eridanus. Only some exceptionally luminous hl-SNRs may be possible to detect up to about ~ 100 Mpc distance (e.g., the Coma cluster).

3.2 *hl-SNR as excess number of radio sources*

Another possibility to detect hl-SNRs could be via estimating number of excess radio sources in galaxy groups or clusters with respect to the average number of background radio source population in the adjacent regions. The number of background radio sources per square degree are expected to be of the order of 10^4 at 10 μJy level and between 10^4 and 10^5 at 1 μJy level (Norris *et al.* 2015). It is assumed here that all other excess radio sources co-located with the nearby galaxies will be subtracted beforehand. The number density of the background radio sources will vary from one region to another due to cosmic variance, which may be assumed to follow a Poisson statistics, i.e., number of radio sources N can vary as $\pm\sqrt{N}$. Therefore, the variation per square degree can be between 100 and 300. Hence, the number of detectable hl-SNRs in majority of galaxy groups or clusters with masses in the range of 10^{13}–10^{14} is always expected to remain comparable to or less than the random variation in the background radio source counts. It may also be noted that the hl-SNR being detectable only at relatively nearby regions, the angular extents of many rich and massive galaxy groups and clusters will be more than one degree. Therefore, the possibility to detect hl-SNRs as excess number of radio sources against the background un-resolved cosmic source population appears feeble. A search made in the NASA Extragalactic Database (NED) for galaxy groups and clusters up to 50 Mpc and 100 Mpc distance results into about 3000 and 10,000 galaxy groups and clusters, respectively. Therefore, an analysis with co-adding the number of radio sources in multiple groups and clusters and then, making a comparison with the background radio source population, may allow to reliably infer presence of a sizeable hl-SNR population in galaxy groups and clusters as excess radio sources.

4. Summary

Some possibilities to detect hostless SNRs in the anticipated deep radio surveys of a large portion of the celestial sky with the SKA were discussed in this paper. The analyses made in this paper suggest that although detections of the hl-SNRs are challenging and demand un-precedented high sensitivity (sub-μJy) combined with a high angular resolution (sub-arcsec), a considerable number of hl-SNRs should be possible to detect in nearby groups and clusters up to a distance of ∼ 100 Mpc. The important findings are summarized below:

(i) The expected number of hl-SNRs in a galaxy group or cluster is estimated to be nearly 25 in a $z \sim 0$ cluster mass of 10^{13} $M_{\odot}$. This number is based on the hl-SN rate estimated from the SDSS-SN survey and assuming that the radio detectability of most SNR will be about 10^4 years. Although this is a rough estimate, it presents a favorable scenario for detection of hl-SNRs with the SKA.

(ii) The hl-SNRs in the local group and its immediate neighbor groups of galaxies can be detected with the SKA. With the highest sensitivity, a considerable number of general population of hl-SNRs may get detected in nearby galaxy groups and clusters, such as Virgo Fornax and Eridanus within a distance of ∼ 25 Mpc.

(iii) Some radio SNRs with exceptionally high luminosity may get detected at larger distances up to ∼ 100 Mpc, e.g., in the Coma cluster.

(iv) The diameter of SNR will vary as a function of the ambient density. In a density of 10^{-4} cm^{-3} expected in IGM and ICM, the radio diameter of an evolved SNR is estimated to be ∼ 200 pc and was taken as a canonical size for SNRs in IGM and ICM.

(v) The low temperature regions of groups and clusters can be expected to provide a favorable environment for detecting hl-SNRs. This is due to relatively high Mach number expected in low temperature ambient medium thereby increasing the particle acceleration efficiency.

(vi) The hl-SNRs need to be partially resolved to allow their identifications via the characteristic morphologies, i.e., circular edge-enhanced.

(vii) The hl-SNRs may also be detected as an excess in the radio source counts in galaxy groups and clusters against the background radio source counts. However, this method will require combining radio source counts of tens or even hundreds of galaxy groups and clusters. In such analyses, all other radio sources co-located with the nearby galaxies need to be subtracted beforehand.

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